

*more complete
than preliminary
memo, dated 1-12-60,
requested*

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Pittsfield, Mass., April 14, 1961

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In order to make Project EHV as successful a venture as possible, much thought must go into planning how to make the data collected from the project as useful from a marketing viewpoint as practicable. It is probably true that if the data were simply resolved into the form of sets of published curves, these curves soon become public property and little but good-will will be gained. However, there are much data of great interest to any EHV system designer that cannot be published as simple curves, since they involve large quantities of statistical interactions. These data remain under our control, stored on tapes or punched cards, and if tied into computer programs or other computation routines, could be of great influence and of considerable economic benefit to any utility that uses them. From the marketing point of view, these computational routines could be of help in obtaining consideration on certain selected orders.

The attached memorandum is an effort of the Project EHV insulation activity to lay the basis for a routine for determining EHV line insulation economics. This routine would forecast the line's insulation performance and compare it with the insulation cost. Being probabilistic in nature, it is aimed toward a Monte Carlo calculating procedure, similar to the one now so successful in predicting line lightning performance. In the view of some, it will probably seem to be too highly refined. However, the data to implement such a method can be obtained, and it is only these refinements that can be used to counterbalance the simpler data that will become public property. The memo is an adjunct to one written last year in an early exploratory effort on the same subject.

The writer would like very much to receive suggestions, comments, and recommendations from those interested.

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OPTIMIZATION OF INSULATION LEVELS IN EXTRA-HIGH-VOLTAGE SYSTEMS - MINIMUM COST FOR A GIVEN RELIABILITY

In 1960, a memorandum entitled "Economic Optimization of Insulation in Electrical Systems" by the writer, was circulated among G.E. people interested in the subject. This memorandum attempted to lay the foundations for an economic approach to insulation design, essentially by choosing insulation levels so that total long-run costs, including initial investments and costs of failures, were minimized. While the memo created considerable interest, there seemed to be almost universal agreement that the total cost of a failure is, in many cases, as much an emotional problem as an economic one. Sensible data on probable failure costs appear to be almost non-existent. If one does not know at what price to evaluate a failure, it follows that one cannot know how much to spend to avoid it. This one fact probably accounts for much of the great variation in insulation levels of similar systems in the industry.

An obvious solution to this problem is to collect failure cost figures. This, however, may take many years and require some changes in accounting practices. Therefore, it is of interest to cast about for other interim methods of optimizing insulation levels that could be used in the immediate future.

Two of the procedures that appear feasible are:

1. Design the insulation system for minimum cost required to attain a given level of reliability. This avoids considerations of costs of failures, except costs of repairs and replacements, trading it instead for a management specification for a specific level of reliability (or availability) acceptable to management.
over the long run.
2. Calculate insulation levels in such a way that, assuming the system is an optimum one, the cost of a failure that is being tacitly assumed can be demonstrated. This cost figure then can be used as a basis for managerial decisions on whether an increase or decrease in insulation level is practicable.

With present practices and attitudes, the first approach is probably easier to implement than the second. Using this approach, two questions actually must be answered:

1. If a given level of reliability is specified, how can this level be achieved at minimum cost?
2. How will the minimum costs vary with reliability requirements?

Question 2 is an important one for management in determining where new investment capital can best be used. This information would be in the form of some kind of curve, a conceptual model of which is sketched in Fig. 1. Management could examine such a curve and decide better whether an improvement in reliability is actually worth the increase in expense. The minimum total cost in Fig. 1 would include all accessible probable direct costs of failures and repairs that can be determined. The only costs it would not include are the emotional ones and those of a highly nebulous nature such as "customer relations" and "damage to the national economy". It is assumed that when management specifies a given level of reliability they are taking these secondary factors into account, since these factors are largely in the realm of human relations rather than engineering decisions.

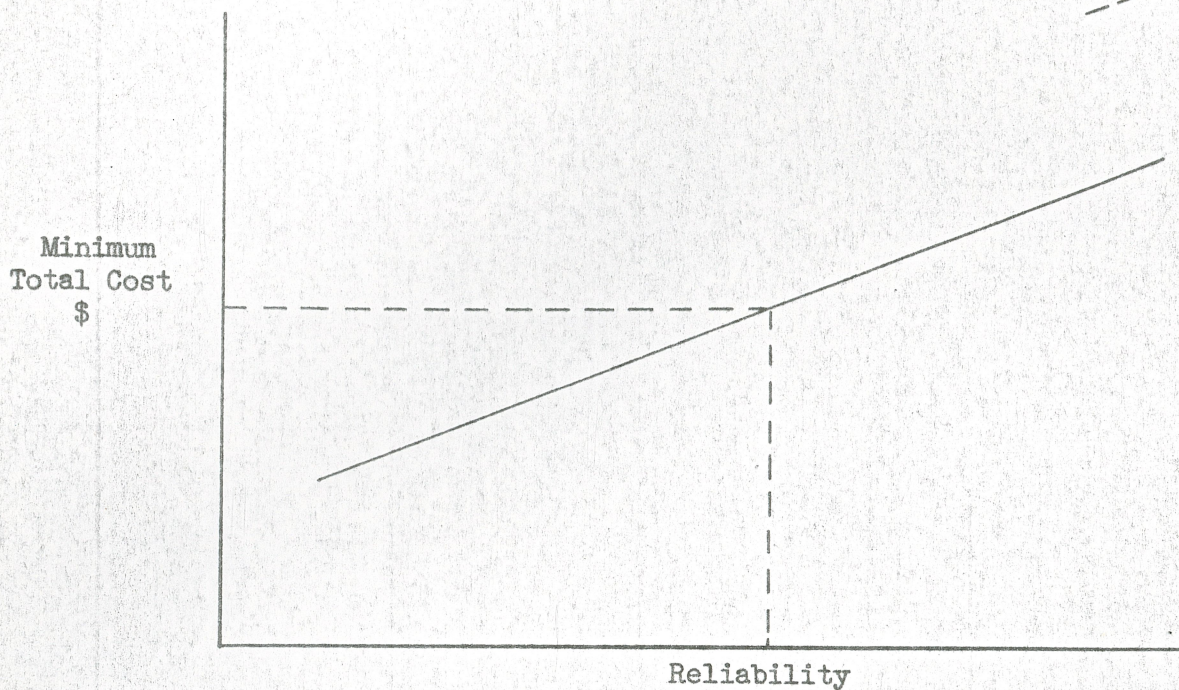


FIG. 1

Definition of Terms

Before such an approach can be discussed, some useful symbolism should be established:

- T = Total designed life time (in days, years, or other convenient units) of an insulation system - the base time.
- t = permissible unplanned outage time of the insulation system.
- p = ratio of unplanned outage time t to the base time T . The system outage rate.
- q = $(1-p)$ = the reliability of an insulation system. The probability that at any time the system insulation will be available to perform its intended function.
- P_a = the probability of no-failure of an element e_a during the designed life time T when stressed in its intended manner.
- C_a = the initial cost of the insulation of element e_a including the installation cost attributable to insulation.
- D_a = the directly determinable costs that would be incurred if element e_a fails. This would include costs of repairs and replacement of all or part of e_a .
- N_a = the probable total number of failures of element e_a that will be likely to occur during the design period T if replacement is made as failures occur.
- n_a = the number of elements of kind e_a that are stressed in the system.
- S_a = the total expected costs, including initial costs and failure costs, of the group of all insulation elements of type e_a .

Definition of Terms (Cont.)

S = total cost, including determinable probable failure costs, of the entire insulation system.

Reliability and Availability

The abscissa of Fig. 1 uses the word "reliability" in its usual relationship - the avoidance of unscheduled outages. If a system has a total unplanned outage time t over some long base period of time T , the outage rate p for the system (planned shutdowns not included) is defined as

$$p = t/T \quad \dots\dots\dots (1)$$

In this memo, reliability is then defined as q , where

$$q = (1-p) \quad \dots\dots\dots (2)$$

Thus, reliability is the probability that the system will be available to perform its intended function when required.

Basic Requirements of the Insulation System

The portion of a system at extra-high-voltage consists of the high-voltage side of the transformers, the station equipment, and the transmission line or lines. This portion contains no active generation, thus considerably simplifying matters. In Fig. 2,

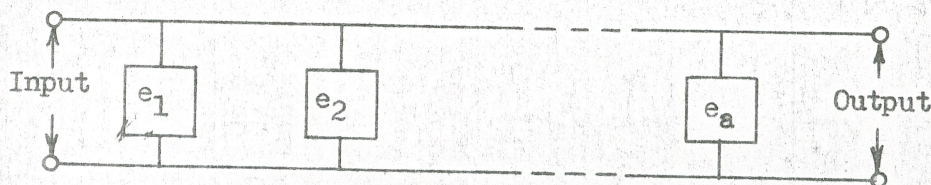


FIG. 2

this extra-high-voltage portion is represented as an input, an output, and a group of elements $e_1, e_2, \dots, e_a$ of as yet undefined characteristics. With this simple diagram, some element and system requirements must be outlined:

1. Each element e_a has a probability of no-failure P_a during a design time interval T (say 20 to 100 years). This probability is some yet undefined function of the voltage levels appearing on the system, and can only be established once these voltage levels are known or predicted.
2. The failure of element e_a will be associated with some mean outage time t_a . (This time t_a will probably be much less for an insulator string - easy to replace - than for a large power transformer - difficult to replace).
3. For each no-failure probability P_a , P_a will be some function f_a of the cost C_a of the element, or $P_a = f_a(C_a)$. In most cases, one can increase the probability of no-failure only if he is willing to pay more to make the element stronger.

4. Any element that fails before time T is achieved must be replaced. There is no prohibition against the replacement also failing in the time that remains.
5. Each element e_a that fails will require a penalty cost D_a to be paid that represents the cost of repairs or replacement of part or all of e_a . A circuit breaker would most likely have a higher penalty cost than a bus insulator.
6. Once the reliability requirements of the system are specified over the base time T, the total unscheduled outage time t is fixed, and the system is to be designed to have this outage time.
7. With this outage time t, the system should be designed for minimum insulation cost. Obviously there may be many combinations of elements $e_1, e_2, \dots e_a$ that will give the same total outage time, but some combinations will be less expensive in insulation requirements than others.

Mathematical Requirements to be Satisfied

In Appendix 1, it is shown that, if n_a elements of type e_a are stressed simultaneously in a system for some total period of time T, and if the probability of each element not failing during this time is P_a , and if furthermore when any failure occurs it is immediately repaired or replaced with a new identical element and the stressing of the elements continued as before, then the total number of failures N_a of elements e_a during the time period T will be

$$N_a = -n_a \log P_a \dots\dots\dots (3)$$

where $\log P_a$ is the natural logarithm.*

The total expected penalty cost $\sum_a D$ of each element e_a will then be the total expected number of failures N_a multiplied by the mean penalty cost of each failure D_a , or

$$\sum_a D = -n_a D_a \log P_a \dots\dots\dots (4)$$

To this total expected penalty cost must be added the initial cost of the insulation C_a of each element e_a to obtain the total cost S_a that will be expected for element e_a , or

$$S_a = C_a - n_a D_a \log P_a \dots\dots\dots (5)$$

The total cost S will then be the sum of the equation (5)'s for all the elements:

$$S = \sum_{a=1}^a C_a - \sum_{a=1}^a n_a D_a \log P_a \dots\dots\dots (6)$$

Now that this expression for total cost has been reached, some required reliability level must be specified for the system. From equation (2), once the required reliability level has been specified, the total permissible unplanned outage time t is established, i.e.

$$t = T [1-q] \dots\dots\dots (7)$$

*This simple relation is probably well known but the writer was unaware of it.

It is simpler to use total unplanned outage time t instead of the term "reliability" because it is more direct. This total outage time t will be the sum of the outage times created by each of the elements, which in turn is the product of the number of outages N_a of each element multiplied by its mean outage time t_a . Then:

$$t = \sum_{a=1}^a N_a t_a$$

or
$$t = -t_1 n_1 \log P_1 - t_2 n_2 \log P_2 - \dots - t_a n_a \log P_a$$

or
$$t = - \sum_{a=1}^a t_a n_a \log P_a \dots \dots \dots (8)$$

Returning for the moment to equation (6) for the total cost S , the term C_a in this equation is in itself a function of the probability P_a of no failure, and it has been stated as $P_a = f_a(C_a)$. In equation (6) the substitution of this term results in an equation that is a function only of the costs C_a and penalties D_a :

$$S = \sum_{a=1} C_a - \sum_{a=1} n_a D_a \log [f_a(C_a)] \dots \dots \dots (9)$$

Similarly equation (8) can be written:

$$t = - \sum_{a=1} t_a n_a \log [f_a(C_a)] \dots \dots \dots (10)$$

The best solution for a set of system insulation characteristics then occurs when values of $C_1, C_2, \dots, C_n$ are chosen so that equation (10) is satisfied [or the right side does not exceed t], and for these chosen values S is minimized. It is extremely difficult to solve equations of this type so that both these requirements are satisfied. In equation (10), for K values of C , $K-1$ can be chosen independently and the K th value is then dependent on t . Once these values are chosen they must be substituted into (9) to solve for S and there is no criterion that this S will be the minimum. It appears far simpler to pick many feasible values of C , many of which will be restricted anyhow, and then solve for the resulting outage time t and cost S . The results can then be plotted as in Fig. 3 below in terms of S and t :

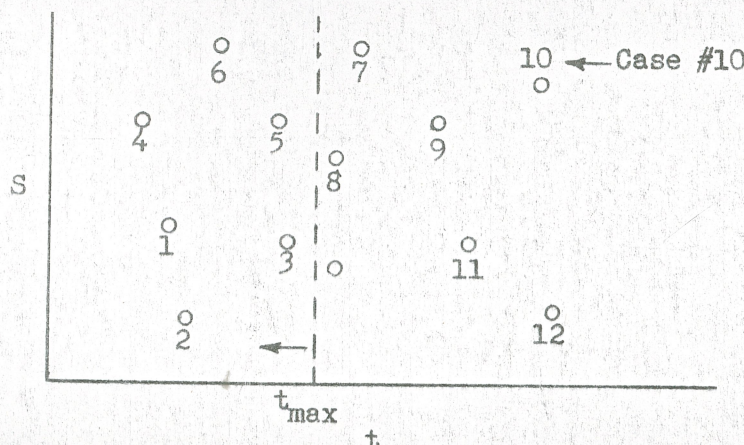


FIG. 3

Only those points less than $t_{\max}$, the specified maximum unscheduled outage time, become admissible designs and of these, the point having lowest value of S is then chosen. This becomes an intelligible way of calculating system insulation provided:

1. A computer can be programmed to determine a large number of trial solutions.
2. The probability of no failure as a function of cost can be determined for each element.

The second requirement is the only really difficult part, and the remainder of this memo will be devoted to consideration of this requirement.

The Problem of Probability and Cost

The probability of an insulation failure (or the lack of it) depends on:

1. Amplitudes and other characteristics of the voltage applied, including its variability and number of applications.
2. Insulation level of the device and its variability.
3. Length of service of the device.
4. Possibility of protection by operation or failure of other devices on the same bus (i.e. bus insulators or a circuit breaker might be protected by flashover of a rod gap on the same bus).

One further complication is the lack of a fixed outage time for some kinds of insulation, particularly line insulation. A large percentage of line flashovers (in regions of moderate or high isokeraunic level) is caused by lightning. Where automatic reclosing is used, these flashovers may not be a serious problem as long as the reclosing is successful. If reclosing is successful $X\%$ of the time (based on past performance), the average outage time t_e would be

$$t_e = \frac{x t_1 + (100-x) t_2}{100}$$

where t_1 = outage time per successful reclosing.
 t_2 = outage time per unsuccessful reclosing.

and it is probably feasible to use this average outage time from the beginning.

The amplitudes and waveshapes of switching voltages on a system can be found from analog measurements and calculations of the system characteristics, once the system has been defined. These amplitudes can then be described in an amplitude-frequency of occurrence curve similar to Fig. 4. If one does not need to be so explicit, only one surge-the maximum- could be used.

(See Fig. 4 on Page 7)

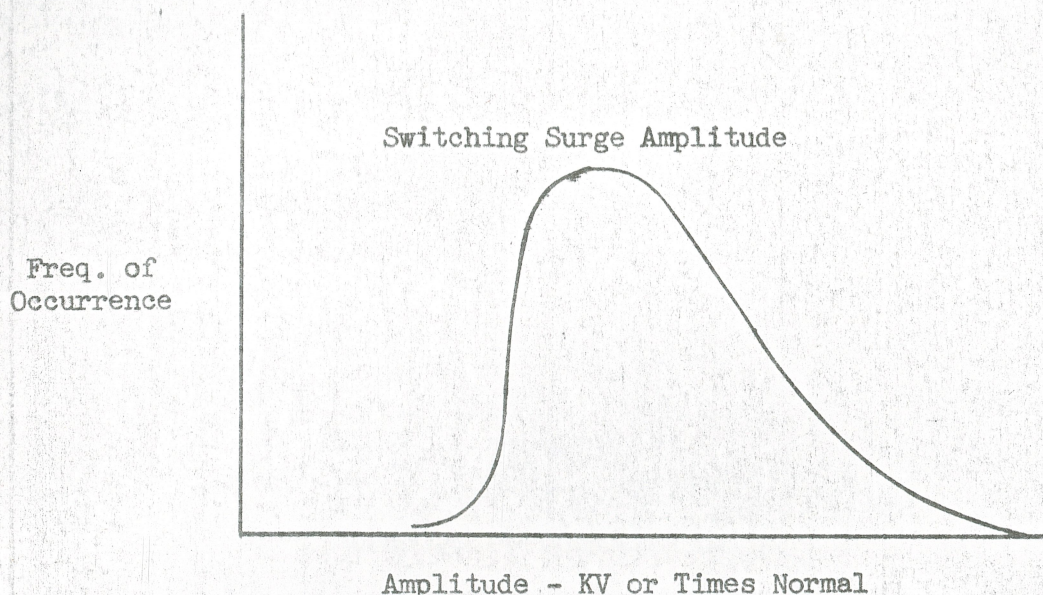


FIG. 4

Attached to each kind of surge could be a weight or sensitivity factor, if required. This would account for the fact that, in many cases, a flashover during deenergizing a line may not be as critical as when one is attempting to energize it. This would be a possible future consideration if, instead of specifying a single reliability, one specifies the reliability under various load conditions.

The variability of insulation strength to withstand the above mentioned voltages is determined to a very large extent by the weather. Weather prediction on a day by day basis many years ahead is impossible (with present knowledge) but the probable over-all behavior over a long period of time can be found from past Weather Bureau records and incorporated into a Monte Carlo routine. The variation in insulation strength with weather is being determined now by Project EHV tests, and these data could be applied to systems at any other location whose weather history is on record.

The insulation strength of line insulation will appear in a cumulative frequency curve similar to Fig. 5, along with appropriate weather modifiers. Curves of this type have another interesting property, that of interchangeability between number of insulators and number of surges applied. For example, if a surge of a given magnitude will flash over an insulator string 10% of the time, i.e. one flashover out of each ten surges applied, then if ten insulators have one surge applied to all of them simultaneously, an average of one failure will occur. This is not strictly true, since for units in parallel, the failure of one will relieve the stresses on the others, but approximately so. Thus for a long transmission line, the line strength will have to be greater than for a short line because of this effect.

Some kind of assessment of the likelihood of steady-state overvoltages must eventually be included; for example, generator overspeed or Ferranti effect when breakers open on a long line.

By the above means, the distribution of overvoltages on a system and their effects on insulation of a specified size can be determined. The insulation size can then be translated into insulation cost, including, for example, the increase in tower steel required when a larger tower insulator is used. The cost can then be compared with the forecasted outage time. This type of insulation evaluation procedure is now being planned for the IBM 705.

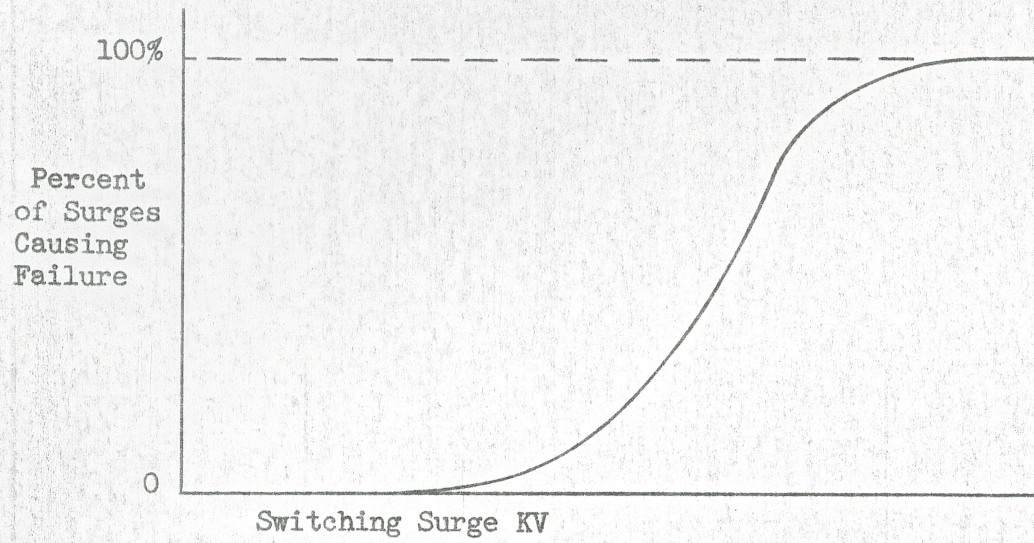


FIG. 5

APPENDIX 1

TOTAL FAILURES UNDER CONDITIONS OF CONTINUOUS REPLACEMENT

Suppose that over a time interval $0 < t < T$, a quantity U of insulator units are stressed simultaneously. If the probability of no-failure for a single unit over the period T is α , then $(1-\alpha) U$ failures will occur that require replacements. However, once these replacements are made, a certain number of the replacements will also fail before the period T is up. When these are replaced, a further percentage of these new replacements will fail, and so on until the end of the period T occurs. What are the total number of failures that will be experienced? The answer will, of course, depend on the assumptions regarding the initial failure rate. If the stress is assumed constant over the period, then this stress can be plotted as in Fig. A below:

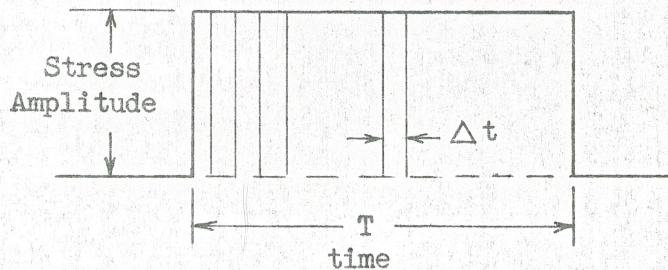


FIG. A

The stress can then be broken up into a set of sequential stresses of duration Δt . If we assume that each insulation unit has no memory of the past and cannot anticipate the future, then the probability of the unit failing during any one element of time dt must be the same as the probability of failure during any other element Δt . It then can be easily shown that if the probability of no-failure over the entire period T is α then the probability of no-failure during time Δt must be $\alpha_{\Delta t}$, where

$$\alpha_{\Delta t} = (\alpha)^{\frac{\Delta t}{T}} \dots\dots\dots (1A)$$

This $\alpha_{\Delta t}$ is very close to unity because $\frac{\Delta t}{T}$ will be very small. If components are replaced as they fail, the total number of components undergoing the stress will always be U , and the total number not failing at any element of time will be $U_n dt$, where

$$U_n dt = U \alpha_{\Delta t}$$

The total number failing $U_f \Delta t$ during time Δt is the total stressed minus the total not failing, or

$$U_f \Delta t = U \left(1 - \alpha_{\Delta t} \right) \dots\dots\dots (2A)$$

But as $\Delta t \rightarrow 0$, $1 - \alpha^{\frac{\Delta t}{T}}$ approaches zero and can be written

$$\lim_{\Delta t \rightarrow 0} \left[1 - \alpha^{\frac{\Delta t}{T}} \right] = \lim_{\Delta t \rightarrow 0} \left[-\log \left(\alpha^{\frac{\Delta t}{T}} \right) \right] = -\frac{1}{T} \log \alpha \, dt$$

*Divide by
 Δt*

Then the number of failures in the limit interval dt is

$$U_f \, dt \approx -\frac{U}{T} \log \alpha \, dt$$

And the total number of failures is U_f , or simply

$$\sum_{t=0}^T U_f \, dt \approx - \int_{t=0}^T \frac{U}{T} \log \alpha \, dt$$

or in the limit

$$U_f = -U \log \alpha \dots\dots\dots (3A)$$

Apr. 17, 1961